AFRL-RX-WP-TP-2008-4047

RESONANT FREQUENCY EDDY CURRENT LIFTOFF MEASUREMENTS FOR SHOT PEENING INTENSITY ASSESSMENT IN MATERIALS (PREPRINT)

Ray T. Ko, Mark P. Blodgett, Shamachary Sathish, and Thomas R. Boehnlein

University of Dayton Research Institute

JULY 2007

Approved for public release; distribution unlimited.

See additional restrictions described on inside pages

STINFO COPY

AIR FORCE RESEARCH LABORATORY
MATERIALS AND MANUFACTURING DIRECTORATE
WRIGHT-PATTERSON AIR FORCE BASE, OH 45433-7750
AIR FORCE MATERIEL COMMAND
UNITED STATES AIR FORCE

REPORT DOCUMENTATION PAGE	*Form Approved* *OMB No. 0704-0188*

The public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Department of Defense, Washington Headquarters Services, Directorate for Information Operations and Reports (0704-0188), 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to any penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number. **PLEASE DO NOT RETURN YOUR FORM TO THE ABOVE ADDRESS**.

1. REPORT DATE ***(DD-MM-YY)***	**2. REPORT TYPE**	**3. DATES COVERED *(From - To)***
July 2007	Conference Paper Preprint	

4. TITLE AND SUBTITLE

RESONANT FREQUENCY EDDY CURRENT LIFTOFF MEASUREMENTS FOR SHOT PEENING INTENSITY ASSESSMENT IN MATERIALS (PREPRINT)

5a. CONTRACT NUMBER F33615-03-C-5219

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER 62102F

6. AUTHOR(S)

Ray T. Ko, Shamachary Sathish, and Thomas R. Boehnlein (University of Dayton Research Institute)
Mark P. Blodgett (AFRL/RXLP)

5d. PROJECT NUMBER 4349

5e. TASK NUMBER 41

5f. WORK UNIT NUMBER 43494107

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

University of Dayton Research Institute
Structural Integrity Division
300 College Park
Dayton, OH 45469-0120

Nondestructive Evaluation Branch (AFRL/RXLP)
Metals, Ceramics & Nondestructive Evaluation Division
Materials and Manufacturing Directorate
Wright-Patterson Air Force Base, OH 45433-7750
Air Force Materiel Command, United States Air Force

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

Air Force Research Laboratory
Materials and Manufacturing Directorate
Wright-Patterson Air Force Base, OH 45433-7750
Air Force Materiel Command
United States Air Force

10. SPONSORING/MONITORING AGENCY ACRONYM(S)

AFRL/RXLP

11. SPONSORING/MONITORING AGENCY REPORT NUMBER(S)

AFRL-RX-WP-TP-2008-4047

12. DISTRIBUTION/AVAILABILITY STATEMENT

Approved for public release; distribution unlimited.

13. SUPPLEMENTARY NOTES

Conference paper submitted to the Proceedings of the 2007 Review of Progress in Quantitative NDE Conference.

The U.S. Government is joint author of this work and has the right to use, modify, reproduce, release, perform, display, or disclose the work. PAO Case Number: AFRL/WS 07-2127, 14 Sep 2007. Paper contains color.

14. ABSTRACT

The shot peening intensity of nickel base materials has been examined with an innovative eddy current measurement. The goal is to provide a nondestructive tool to quantitatively evaluate the surface conditions after shot peening. Traditionally, the residual stress caused by the shot peening process can be examined by X-ray diffraction. Recent eddy current works have shown promising results in evaluating the small conductivity variation due to the residual stress. This study explores the feasibility of utilizing the cable which connects to a network analyzer and a conventional eddy current probe to monitor the surface conditions due to the shot peening.

15. SUBJECT TERMS

Resonant Frequency, Eddy Current, Liftoff, Shot Peening

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT:**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON** (Monitor)
a. REPORT	**b. ABSTRACT**	**c. THIS PAGE**			Mark P. Blodgett
Unclassified	Unclassified	Unclassified	SAR	14	**19b. TELEPHONE NUMBER** *(Include Area Code)* N/A

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std. Z39-18

RESONANT FREQUENCY EDDY CURRENT LIFTOFF MEASUREMENTS FOR SHOT PEENING INTENSITY ASSESSMENT IN MATERIALS

Ray T. Ko, Mark P. Blodgett[1], Shamachary Sathish, Thomas R. Boehnlein

[1] Metals, Ceramics, and NDE Division, Air Force Research Laboratory,
Wright-Patterson Air Force Base, Dayton, Ohio 45433

Structural Integrity Division, University of Dayton Research Institute,
300 College Park, Dayton, Ohio 45469-0120

ABSTRACT. The shot peening intensity of nickel base materials has been examined with an innovative eddy current measurement. The goal is to provide a nondestructive tool to quantitatively evaluate the surface conditions after shot peening. Traditionally, the residual stress caused by the shot peening process can be examined by X-ray diffraction. Recent eddy current works have shown promising results in evaluating the small conductivity variation due to the residual stress. This study explores the feasibility of utilizing the cable which connects to a network analyzer and a conventional eddy current probe to monitor the surface conditions due to the shot peening.

Keywords: Resonant Frequency, Eddy Current, Liftoff, Shot Peening
PACS: 81.70.Ex

INTRODUCTION

The liftoff parameter, which is defined as the distance between a probe and the material under test, is usually considered as an undesirable variable in eddy current testing. For example, a common practice in typical flaw detection is to rotate the liftoff signal in the horizontal channel of the impedance plane while observing signals in the vertical channel. Therefore, the impact of liftoff variation by the movement of the probe in an inspection is reduced. Research using the liftoff curve itself is sporadical and control of the liftoff signal remains a problem even for today's advanced eddy current instrumentation. For example, in pulsed eddy current (PEC) testing, the liftoff is avoided by using a LOI (liftoff point of intercept) approach. At this point, the signal amplitude is independent of the liftoff. Numerous measurements have been reported using this LOI. On the other hand, by varying the distance between a probe and the material, one could obtain valuable information of the material's property. This is because for each material or conductivity, there exists a unique liftoff curve in the impedance plane, as shown in Figure 1.

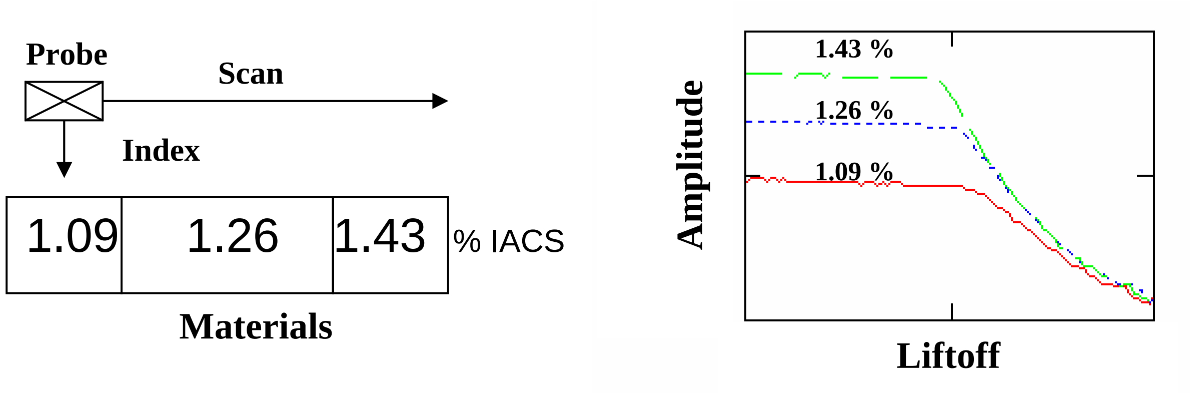

FIGURE 1. The liftoff signals of materials of three different conductivities. Conventional eddy current is sensitive to large liftoff and conductivity variations.

For shot peened materials, the change of apparent eddy current conductivity due to the shot peening process is typically less than a percent or one-hundredth of % IACS (International Annealed Copper Standard). With conventional eddy current, which is built primarily for crack detection, it is difficult to distinguish a lightly shot peened surface, such as those from an engine component, from an un-peened one. Consequently, to address the shot peened level determination, as well as the residual stress estimation [1], several approaches have been developed to address this need for small conductivity measurement at high frequencies.

Unlike most of the approaches which use innovative coil configurations for high frequency measurements, this resonant frequency approach [2, 3] explores the idea of using a cable, which connects between a probe and an instrument, as a resonator in generating high frequency eddy currents. The frequency range of a typical network analyzer used here is from KHz to GHz. The high frequency of this instrument is well beyond the commercial eddy current instrument high-frequency-limit of 12 MHz.

In addition, this paper also explores the concept of using the liftoff curve for a quantitative measurement of material property. Experimental data are provided to show that the liftoff curve could be a powerful tool in a quantitative eddy current measurement. A simple equivalent circuit is provided as a basis for the experimental observation.

AN EQUAIVALENT CIRCUIT FOR RESONANT FREQUENCY

Figure 2 shows a simple equivalent circuit resonant frequency measurement. The material under test is treated as a single turn coil with resistance in the secondary circuit [4]. Let R_1 be the resistance of the inspection system including both cable and coil and L_1 the inductance of the primary circuit, while L_2 is the inductance and R_2 is the resistance of the secondary circuit. I_1 is the current in the primary circuit and I_2 is the current in the secondary circuit. M is the mutual inductance between these two circuits. This mutual inductance is closely related to the coupling condition between two circuits. A large liftoff gives small coupling constant while a small liftoff gives large coupling constant. A sinusoidal frequency, ω, is applied to the primary circuit across capacitance C which is mainly due to the cable.

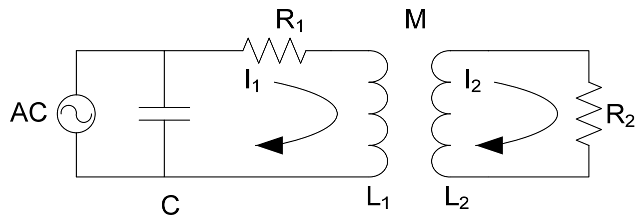

FIGURE 2. An equivalent ciruit showing an eddy current inspection on a material.

At high frequency [5], or when $\omega L_2 / R_2 >> 1$, it follows that a resonance occurs when the impedance becomes purely real and the imaginary part of the impedance reaches zero, the inductive and capacitive portions of the circuit become

$$0 = \frac{1}{j\omega C} + j\omega L_1 (1 - k^2) \tag{1}$$

where k is the coupling coefficient commonly defined as $k = M / \sqrt{L_1 L_2}$ with M the mutual inductance of the circuit. Therefore, the resonant frequency, ω becomes

$$\omega = \frac{1}{\sqrt{L_1 C (1 - k^2)}} = \sqrt{\frac{L_2}{(L_1 L_2 - M^2) C}} \tag{2}$$

when the coupling between the two circuits reach the minimum, i.e., $k = 0$, the resonant frequency simply becomes $\omega = 1 / \sqrt{L_1 C}$.

EXPERIMENTAL SETUP

The cable is an integral part of an eddy current inspection system. The stray capacitance in a cable which connects to a probe is typically small. Although the cable effect has often been neglected in conventional eddy current testing, it still could have some impact on the signal acquired. For example, excessive movement of a cable during a test or changing to a cable of different length could cause changes in the signal. In addition, the effect of the cable needs to be closely examined when measuring material properties very close to surface, or at high frequencies.

Figure 3 shows the variation of the resonant frequency with the length of the cable. Notice that as the cable length increases, the resonant frequency decreases. Although in conventional eddy current testing where a typical 6-foot cable is used, the resonant frequency due to the cable is about three times the highest frequency of conventional eddy current instruments. The cable effect becomes more significant as the test frequency is increased.

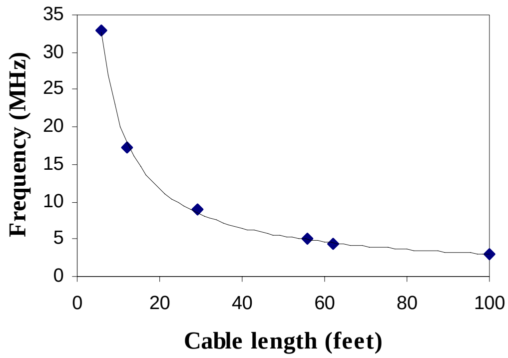

FIGURE 3. Example of cable length vs. resonance frequency.

Unlike an impedance analyzer which allows measurement of a device over a wide range of impedance, a network analyzer is designed for the measurement at specific characteristic impedance. In a previous study, a novel eddy current technique utilizing this cable effect for high frequency measurements using a network analyzer was reported. The impedance mismatch between an eddy current probe and the network analyzer creates a reflected signal and thus a standing-wave pattern. As the coupling condition of the probe changes, the amplitude and the phase of the signal also changes.

The scattering coefficient, as measured by a network analyzer, is the ratio of reflected wave to the incident wave in a simple one-port case. It has a direct relationship between the electrical impedance of the material being interrogated and the characteristic impedance of the measurement system. Therefore, the parameters which affect the impedance could also change the scattering coefficients and vice versa.

Figure 4 shows the experimental setup. The frequency is recorded when a sharp phase change occurs in the scattering coefficient. As the cable length increases, the resonant frequency decreases. This shift of the resonant frequency is sensitive to conductivity, liftoff, defects …etc.

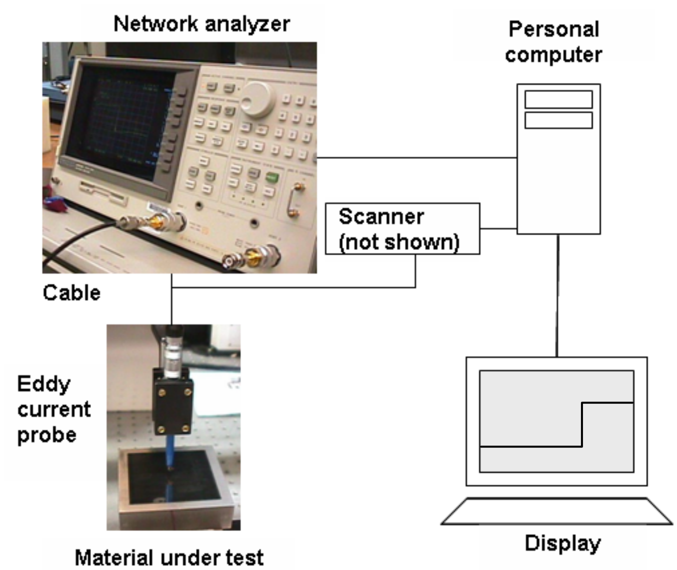

FIGURE 4. The experimental setup used for resonant frequency eddy current liftoff measurements.

RESONANT FREQEUNCY EDDY CURRENT LIFTOFF MEASUREMENT

The resonant frequency eddy current liftoff curve is made by recording the resonant frequency at different liftoff positions. The frequency shift is the difference of the resonant frequency between the peened side with the un-peened side of the specimen. Figure 5 shows the experimental results of materials with various shot peening intensities.

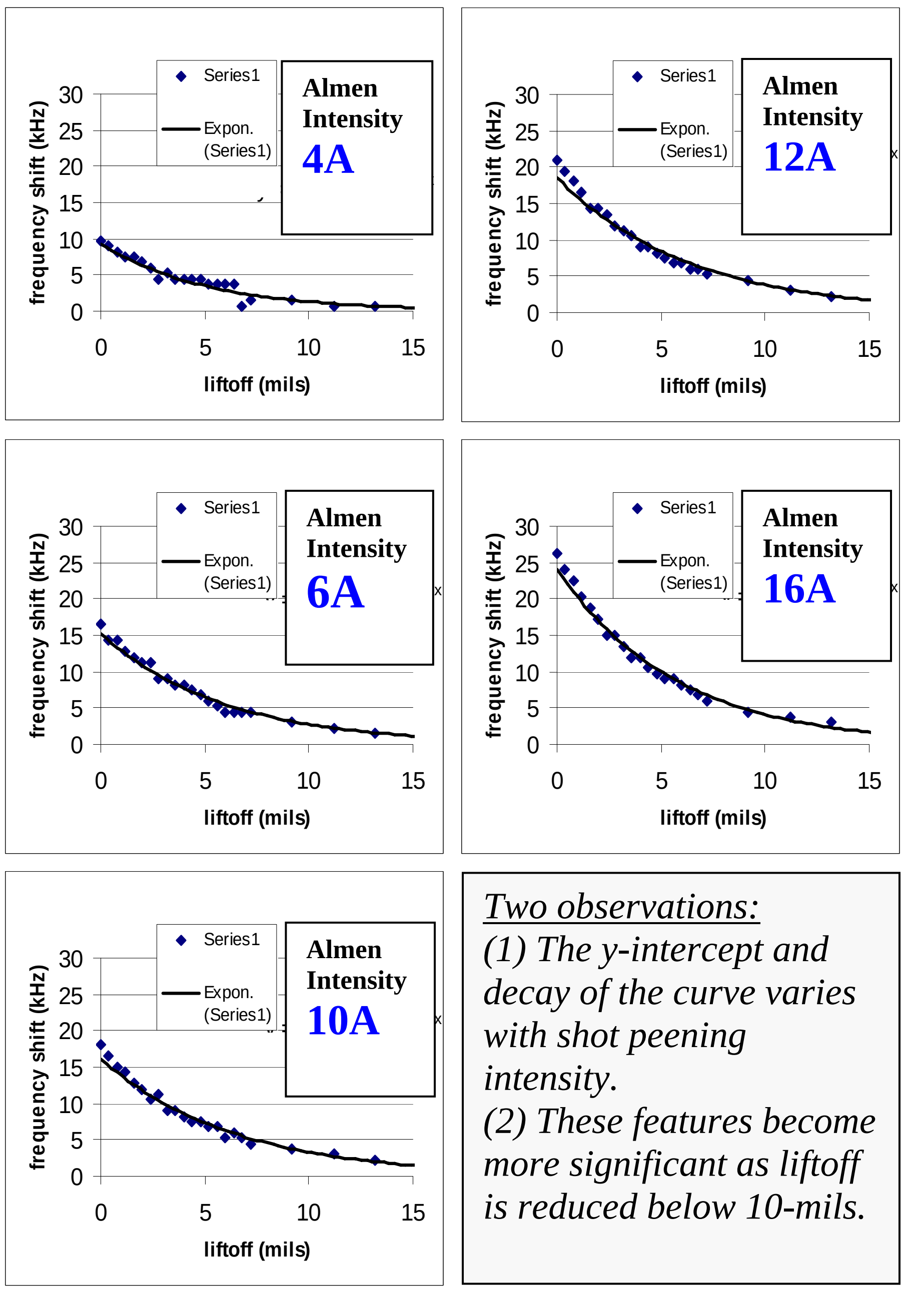

FIGURE 5. Experimental data showing the resonant frquency at different liftoffs for materials of differnet shot peening intersity. Each series of data is fitted with an exponential curve. An Almen strip of "A" type is used to moinitor the shot peening intensity. The heaviest intesntiy tested is Almen 16A.

MONITOR SHOT PEENING CONDITIONS

The curves in Figure 5 show that high shot peening intensity has a larger y-intercept and a larger decay rate. Both of these trends could be used to monitor the shot peening conditions of materials. The following steps outline this process in Figure 6. Figure 7 illustrates the Steps 1 and 2 showing resonant frequency data at two liftoffs and a fitted curve.

The monitoring of shot peening condition is described in Step 3 in Figure 6. It requires an interpolation of the measured resonant frequency to a pre-determined experimental curve to identify the shot peening condition. This experimental curve can be constructed by using either the y-intercept or the decay information from curves of known shot peening intensities as shown in Figure 5.

For example, using the intercept at y-axis and shot peening data in Figure 5, a correlation curve can be constructed. This is shown in Figure 8. With this correlation curve, the shot peening condition of an unknown material can be evaluated by using the y-intercept c_1 to this correlation curve. Figure 8 uses two arrows to illustrate this process.

Step 1. Measure the resonant frequency (y) at two liftoffs (x)

↓

Step 2. Solve for two constants c_1 and c_2 in the following equation:

$$y = c_1 * \exp(-c_2 * x)$$

↓

Step 3. Interpolate c_1 on an experimental curve to identify the shot peening condition

FIGURE 6. A flowchart shows the evaluation of unkonwn shot peening condition from experimental data.

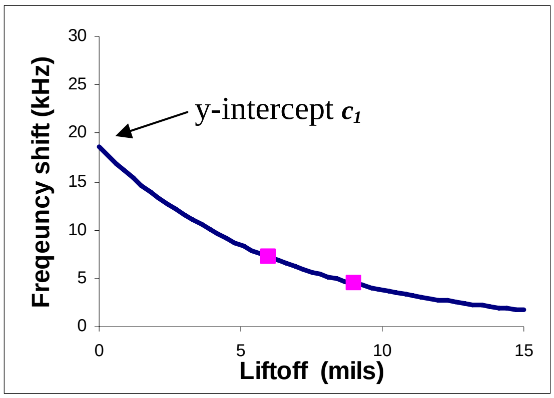

FIGURE 7. Based on resonant frequency data at two liftoffs, a curve is fitted, based on a simple equation described in Step 2 in the text. Both the y-intercept c_1 and decay c_2 can be obtained.

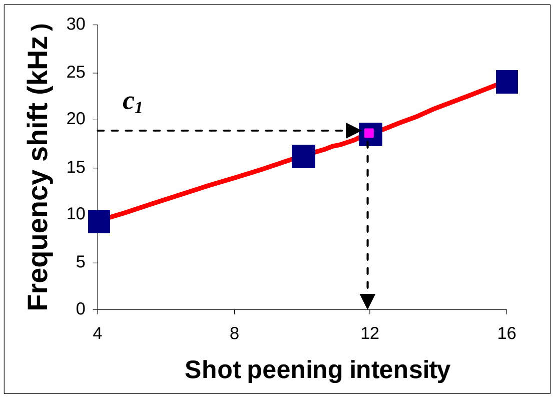

FIGURE 8. Using the y-intercept c_1 from a fitted curve and a correlation curve from the experimental data, the interpolation gives the estimated shot peening intensity of materials under test.

CONCLUSIONS

The feasibility of utilizing the cable which connects to a network analyzer and a conventional eddy current probe to monitor the surface conditions due to the shot peening has been explored:

- A novel resonant frequency eddy current measurement technique at high frequencies has been developed.
- This novel eddy current measurement technique monitors the frequency at which a sharp phase change occurs.
- As the cable length increases, the resonant frequency decreases.
- An application has been presented that monitors the surface treatment conditions of shot peened materials.
- At high frequencies, the surface conditions were easily distinguishable using the frequency shift measurement.
- The resonant frequency liftoff measurement technique discriminates shot peened materials of different intensities from Almen 16A to 4A.
- Assessment of shot peening conditions can be made by using the resonant frequency data obtained at only two liftoffs.

ACKNOWLEDGEMENTS

This work was performed on-site in the Nondestructive Evaluation Branch of the Air Force Research Laboratory (AFRL/MLLP) at WPAFB, Ohio, under Air Force contract # F33615-03-C-5219.

REFERENCES

1. Mark P. Blodgett and Peter B. Nagy, "Eddy Current Assessment of Near-Surface Residual Stress in Shot-Peened Nickel-Base Superalloys," *Journal of Nondestructive Evaluation*, Vol. 23, No. 3, pp. 107-123 September (2004).
2. Ray T. Ko, Mark P. Blodgett, Shamachary Sathish, Thomas R. Boehnlein, "A Novel Multi-frequency Eddy Current Measurement Technique for Materials Characterization," *Review of Progress in Quantitative Nondestructive Evaluation*, Edited by D.O. Thompson and D.E. Chimenti, American Institute of Physics Conference Proceedings, New York, Vol. 25A, pp. 415-422 (2005).
3. Ray T. Ko, Mark P. Blodgett, Shamachary Sathish, Thomas R. Boehnlein, "Application of Resonant Frequency Eddy Current Technique on a Shot-peened Nickel-based Engine-grade Material Novel," *Review of Progress in Quantitative Nondestructive Evaluation*, Edited by D.O. Thompson and D.E. Chimenti, American Institute of Physics Conference Proceedings, New York, Vol. 26B, pp. 1608-1615 (2006).
4. V. S. Cecco, G. Van Drunen and F. L. Sharp, *Eddy current manual*, Atomic Energy of Canada (1983).
5. C. N. Owston, "A high frequency eddy-current non-destructive testing apparatus with automatic probe positioning suitable for scanning application," Journal of Physics E: Scientific Instruments, Vol. 3, pp. 814-818. (1970).